Comparison of the Chemical Evolution of Simulated Milky-Way Type Galaxies

Research Thesis

Presented in partial fulfillment of the requirements for graduation *with research distinction* in in the undergraduate colleges of The Ohio State University

By

Devin Bennett

The Ohio State University

Project Advisor: Professor Jennifer Johnson, Department of Astronomy

Introduction

Galactic simulations allow us to understand the ways in which a galaxy evolves. In simulations, we can quantitatively analyze the effects of different galactic processes in a single galaxy over time. The chemical enrichment of a galaxy is one way to understand such evolution, as the factors that change it can have other impacts on the structure and makeup of the galaxy as a whole.

An important aspect of the chemical composition of the galaxy is the metal to hydrogen abundance. Both the ratio of number of iron to hydrogen atoms ([Fe/H]) and the ratio of oxygen to hydrogen atoms ([O/H]) can reveal important information about the current state of galaxies. Supernovae, for example, eject a large number of heavy elements into the surrounding interstellar medium. Therefore, if there is a high metal abundance in the gas of a galaxy, there may be an above-average amount of supernovae happing in the galaxy at once. Furthermore, if the gas in the galaxy is evolving separately from the gas outside of it, a rapid accretion of new gas with a different [O/H] into the galaxy would also change the average abundance of these ratios.

The ratio of elements formed via the triple-alpha process to iron ([alpha/Fe]) is also important. The two main varieties of supernovae, core-collapse supernovae (CC SN) and supernova Type Ia (SN Ia) occur under very different circumstances and produce different elements. CC SNs occur when a high-mass star runs out of fusible material in its core, and releases mostly alpha-process elements into the surrounding interstellar medium (ISM). SN 1findas, on the other hand, occur due to the thermonuclear explosion of a white dwarf, a process which converts the mass of the white dwarf into iron and similar elements. As such, the vast majority of ejecta from a SN Ia is iron. Since CC SN occur in high mass, and therefore young stars, and SN Ias occur in old stars that have already ended their life on the main sequence, if there is a high [alpha/Fe] in the gas, this may indicate that there is currently an unusually high number large, young stars being formed and subsequently dying, or a “starburst” event.

Through galactic simulations, we might be able to quantitatively analyze the magnitude of the effects that these processes have on the galactic abundance. We can then compare the abundances found in these simulated galaxies to the observed abundances in real galaxies, and from that, make a prediction of the internal processes or the merger history of that observed galaxy.

My goal is to understand how these factors interact with the chemical abundance in greater detail. Specifically, I seek to understand what may cause changes in the ratio of alpha elements to iron. The phenomenon that may cause these changes might leave lasting effects on a galaxy beyond the chemical abundance. By observing these lasting features, it might be possible to deduce the evolution of the galaxy.

In this thesis, I examine the chemical evolution of galaxies simulated by Vincenzo & Kobayashi (2018) in terms of the alpha to iron ratio. I identify the key ways in which the alpha to iron evolution deviates from the simplest case. I then categorize these features and present explanations for their cause.

From Dr. Vincenzo, I received hydrodynamical simulations of 10 Milky Way-like galaxies. The simulation data was divided among 10 zoom regions, each containing an evolving galaxy. Each region had 498 simulation snapshots, or “frames”, representing a cubic region in space, with a side length of roughly 10 to 15 kpc. Each simulation frame was a file that could be unpacked into an object of 34 separate arrays. These 34 arrays came in three varieties: information about the gas particles, information about the star particles, and other information about the galaxy or the state of the simulation.

There are three types of particles within the full hydrodynamical simulation: gas, star, and dark matter particles. In the bulk of the simulation data I was given, information about the dark matter was not included. Because of this, and as I was only interested in the chemical evolution of the galaxies, I concerned myself with the star and gas particles.

Each gas particle represents a homogenous area of gaseous interstellar medium. I had information about the coordinates and velocity of each particle, as well as the mass of the particle, the mass fractions of hydrogen, oxygen, carbon, nitrogen and iron within the gas particles, the density of the gas, the star formation rate (SFR) of the particle, and its identifier (ID).

Each star particle is a representation of a large stellar population. I had information about the current mass of the star particle, the time the population was born, the coordinates and velocity of the particle, the ID of the gas particle it was born from, and the mass contributions of the same elements as in the gas.

The other data arrays in each frame included the coordinates of the center of the galaxy, the age of the universe, and the redshift of the galaxy. A file containing further information, such as the initial mass, of every particle in the full simulation was given, but was not divided into regions/galaxies, nor simulation frames.

Methods

I primarily explored the chemical evolution in terms of the alpha to iron ratio of the gas. To do this, I found the mean ratio of oxygen atoms to iron atoms ([O/Fe]) of the gas in the galaxy, as oxygen is the most abundant alpha-process element reported in the simulations. To get the chemical abundances, I use these equations equation:

$$[\mathrm{O/H}] = \log_{10}(\frac{M_O/\mu_O}{M_H}) - [O/H\ (sun)]$$

$$[Fe/\mathrm{H}] = \log_{10}(\frac{M_{Fe}/\mu_{Fe}}{M_H}) - [Fe/H\ (sun)]$$

$$[\mathrm{O}/Fe] = [O/H] - [Fe/H]$$

where M_O is the mean mass of oxygen, M_{Fe} is the mean mass of iron, μ_O and μ_{Fe} are the atomic masses of oxygen and iron respectively, M_H is the mean mass of hydrogen, and [O/H(sun)] and [Fe/H (sun)] are the elemental abundances of oxygen and iron in the sun. The solar values were taken from Asplund (2009). Due to a difference in normalization, the solar values are subtracted by 12.

Each galaxy, though they are all Milky Way-like spiral galaxies, had a different formation history. Since the abundance ratio is dependent on the gas present, understanding the merger history is an important part of understanding the chemical evolution of a galaxy. When looking at a 3-dimensional representation of the galaxies in time, it is obvious that there are different merger and accretion events. To define precisely when these occur, I examined a simulation frame after a specific time had passed. This timestep was chosen to be 100 million years, as that is the largest timestep between simulation frames. If, over the course of the time step, the mass of the galaxy had grown by more than 10%, I identify an “accretion event” as having taken place at that frame.

New infalling gas isn't the only contributor to the evolution of the galaxies. Ejecta from supernova have a high amount of metals when compared to the surrounding gas. This ejecta mixes with the gas and changes the abundance of the galaxy. As previously stated, I categorized the supernova of the galaxies as two types: supernova Type Ia's (SN Ia), which in this simulation are determined by the single degenerate model(i.e., they occur when a white dwarf star reaches the Chandrasekhar mass), and core-collapse supernova (CC SN), which occur during the death of a star that has a mass greater than 8 Msun. In order to understand the supernova history of each galaxy , I do the following:

First, I find the initial masses of all the star particles in each frame. The initial masses of each star particle were given in a separate file, and the data needed to be extracted from it, along with identifying information. After extracting these lists, I search these lists at each simulation frame to connect each star particle in the frame with its initial mass. In this way, I build an array of initial masses that correspond to the star particles in the frame. I do this for each frame in each galaxy.

I use these initial masses, as well as the age of each star particle, to find the supernova rates of each star particle in each frame. I also find the total number of supernovae that happened since the previous simulation frame.

The number of core collapse supernova produced by a star particle is given by this formula, provided by Dr. Vincenzo:

$$N = M_i \int_{8\,Msun}^{80Msun} m * IMF(m)dm$$

where N is the number of supernovae, M_i is the initial mass of the star particle, and *IMF(m)* is the initial mass function. For simplicity, I used the Salpeter (1955) IMF. The limits of integration represent the mass range of that have died in a supernova - 8 solar masses being about the minimum mass needed to undergo a supernova, and 80 solar masses being the maximum.

The above formula is for the total over core collapse supernovae the course of the star particles life. To calculate the number of supernovae in a specific range of time, this mass range must be calculated from the age of the star particle. The age of each particle in the frame is calculated by subtracting the age of the universe from the birth time of the star particle. The current age of the particle gives the lower bound of masses that would have gone supernova over the course of the frame. To find the upper bound of masses, the age of the particle when the frame started must be found. This is found by subtracting the timestep of the simulation frame from the age of the particle. The timestep of the simulation frame is found by subtracting the age of the universe in the previous frame from current age of the universe. The bounds on the masses of stars that have gone supernovae is found from the two ages using the of the inverse stellar lifetime function given in Padovani & Matteucci (1993), again for simplicity. If the "lower age" is negative, then the star particle must have been born during the simulation, and its lower age is set to 3 million years, about the lifetime of an 80 Msun star. If the star at current time is younger than this, the supernova rate it set to zero, as the stars have not lived long enough to die in a supernova yet. If the current age is more than 30 million years, approximately the lifetime of an 8 Msun star, then the star particle is too old for any more stars to die in a supernova, and again, the core collapse supernova rate is set to zero. Otherwise, then the total CC supernova can be calculated using the formula above.

If CC SN did occur in the particle during that frame, the CC SN rate (in number per year) of the star particle was found by dividing by this amount by the timestep of that frame. If the star was born in that frame, then the rate was divided by the age of the particle. Since both the calculation of the total supernova and this supernova rate require there to be a previous frame to calculate the timestep, these calculations are not done on the first frame of the simulations.

The Type Ia rate of a particle was computed using the following formula, also provided by Dr. Vincenzo:

$$R(t) = M_i * 2 \ * 10^{-3} * t^{-1.1}$$

where *R(t)* is the number of Type Ia supernova per year of the star particle, $t^{-1.1}$ is the delay time distribution function (DTDF), and *t* is the age of the particle in years. Star particles below a certain metallicity threshold [FE/H] < -1.1 have a Ia rate of 0 . Like before, I find the SN Ia rate of all star particles in the frame.

I then find the total SN Ias that happen in the frame by integrating the DTDF from the age of the particle at the beginning of the frame to the age at the end of the frame. I use the age range used to determine the total CC SNs. Again, since this requires a previous simulation frame, I did not perform this calculation on the first frame.

Since the CC SNs primarily eject alpha elements and SN Ias primarily eject iron, an important metric in the [O/Fe] is the ratio of total Ias to total core collapse supernova, the SN ratio. I found this by summing the total amount of SN Ias that happen across the galaxy within a frame and dividing this value by the same sum for CC SNs.

If I feel that binning data would allow for clearer long – term relationships within the graphs, I find the number of frames that correspond to a specific timestep. I then find the mean of the value in question across the frames in that timestep and would graph it against the mean universe time of the selected frames.

The chemical evolution of gas in a galaxy might be different depending on the galactic radius. I find the galactic radius of any given particle using the Pythagorean distance formula:

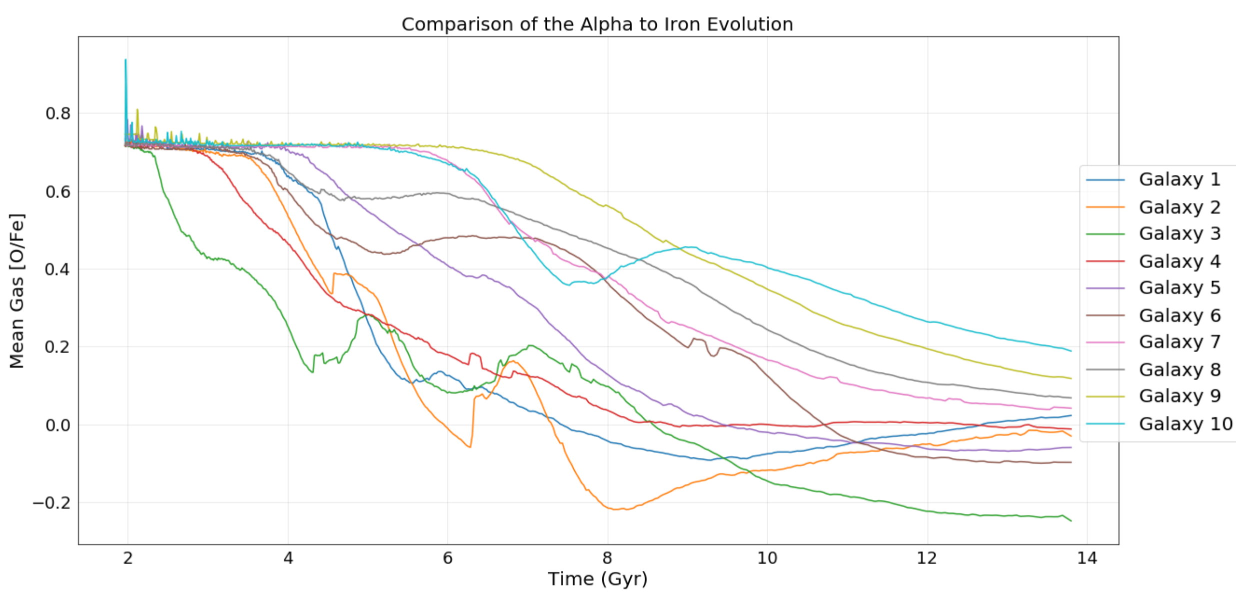
$$R = \sqrt{(X - C_x)^2 + (Y - C_y)^2 + (Y - C_y)^2}$$

Where X, Y, and Z are the coordinates of the particle, and C_x, C_y, C_z are the coordinates of the center of the galaxy.

Results

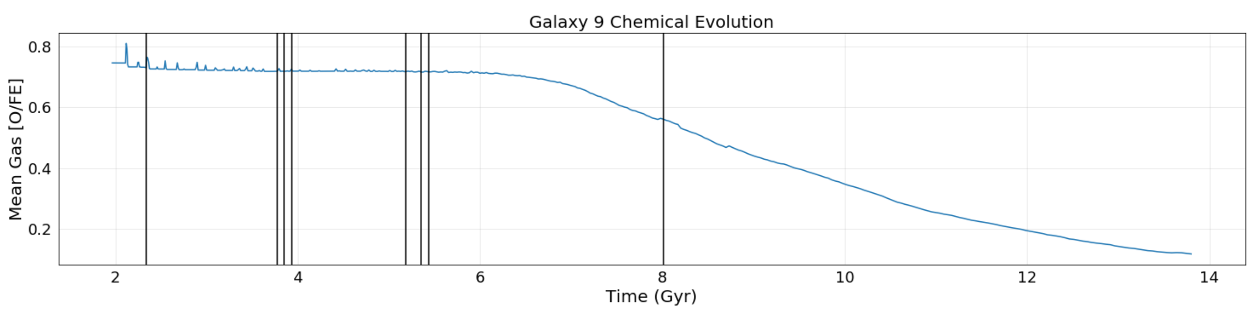
By the end of simulations, there was between 1500 and 2500 gas particles per galaxy. However, the number star particles ranged from 3200 to 34,000. The most massive galaxy was galaxy 3, with a total mass of approximately 10e10 Msun. The least massive was galaxy 9, with a mass of 1.8e10 Msun. The final [O/Fe] ranged between -0.2 and 0.19, and the final [O/H] ranged between -0.1 and 0.09.

Below are the [O/Fe] histories of all 10 galaxies:



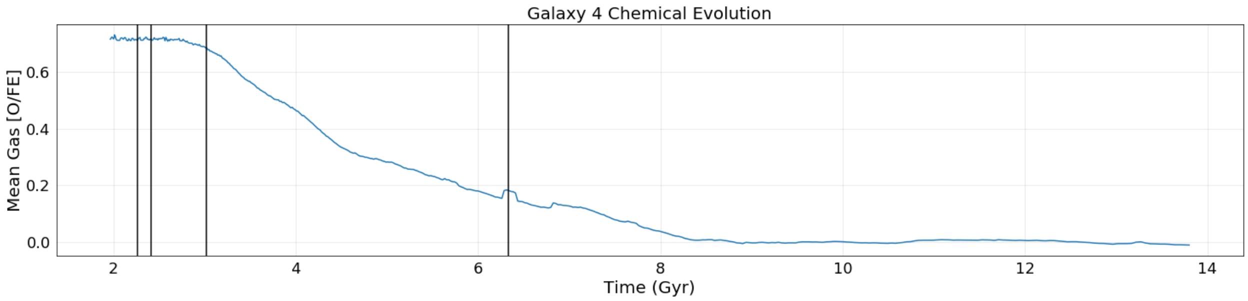
All 10 galaxies begin at the same ratio, and trend downwards over time until they reach an equilibrium ratio, where upon it the curve begins top level off. With the exception of galaxy 2, they begin their trend downwards with a “knee”. Before this point, the trend is flat in time. It should be noted that the galaxies at early times, about when the age of the universe is less than 4 billion years old, there are very few particles in the simulation frames, on the order of 10 per type. Because of this, relatively small changes in mass at earlier times are given far greater weight than the same changes at later times.

Of the 10 galaxies shown, I identified five that best represent the variety of evolutionary histories. These are galaxies 1, 2, 4, 6, and 9. Of these, galaxy 9 was taken as the generic example, due to its similarity to theoretical models produced by Andrews, et al. (2017). It has a flat ratio at early times beyond the unstable reason discussed above, as well as a gentle and well-defined downward trend, before flattening off at later times. Its trend is shown below:



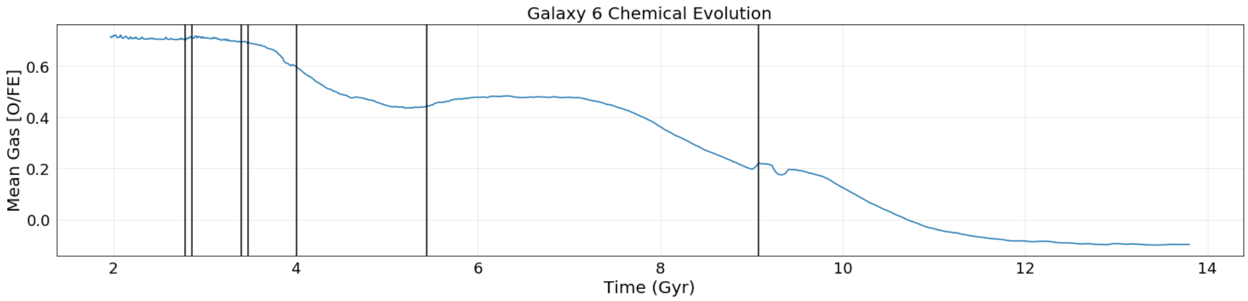
The black vertical lines on this graph, and all subsequent graphs, represent where an accretion event took place. Again, at early times earlier than 4 billion years, these lines can be safely disregarded due to how sensitive the total mass of the galaxy is to minute changes.

There is another accretion event at later times, at about 8 billion years. The effect of this merging even is very slight: the ratio trend appears to carry on as if nothing had happened. However, there is a slight effect associated with it: a small bump, or inflection point where the ratio jumps suddenly. This effect can be seen more clearly in galaxy 4:



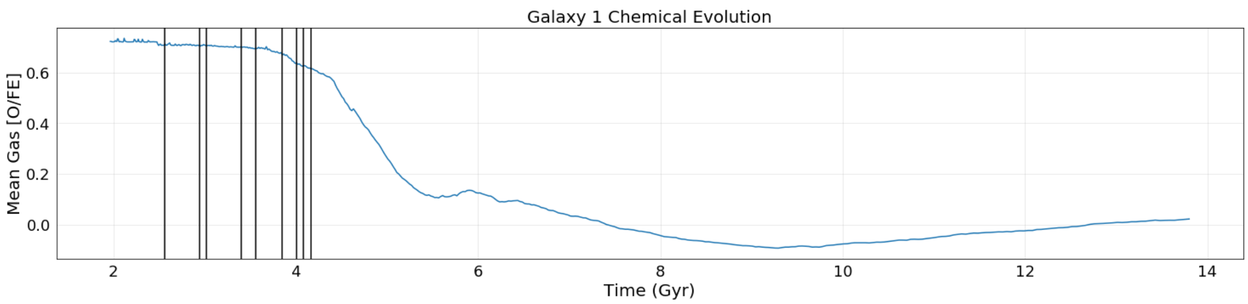
Here, there are three parts of this inflection: the first bump or increase in [O/Fe], the sudden return to baseline, and the final increase that undoes the return to baseline. These inflections, and all inflections with this three-part pattern, are associated with an accretion event. For this reason, I believe these are infections occur when a large mass of gas enters the frame. This gas as a higher [O/Fe] than the host galaxy, thus the ratio is suddenly raised. There is a possibility that the accreting mass may pass through the galaxy and exit the frame. In this case, the [O/Fe] returns to that it was before, as the accreting mass is no longer accounted for. After this, gas will return at a slighter later time and finish merging with the galaxy, suddenly and permanently increasing the [O/Fe] ratio.

There is another feature I found to be associated with accretion events. As previously stated, the galaxies follow a long term decrease in [O/Fe]. If there is an accretion event during this decrease, it is common for the decrease of [O/Fe] to "flatten out." There are a few cases where the [O/Fe] even begins to increase on longer periods of time than the inflections previously seen. I classify this type of feature as a "plateau." A good illustration of this effect is the evolution of galaxy 6:



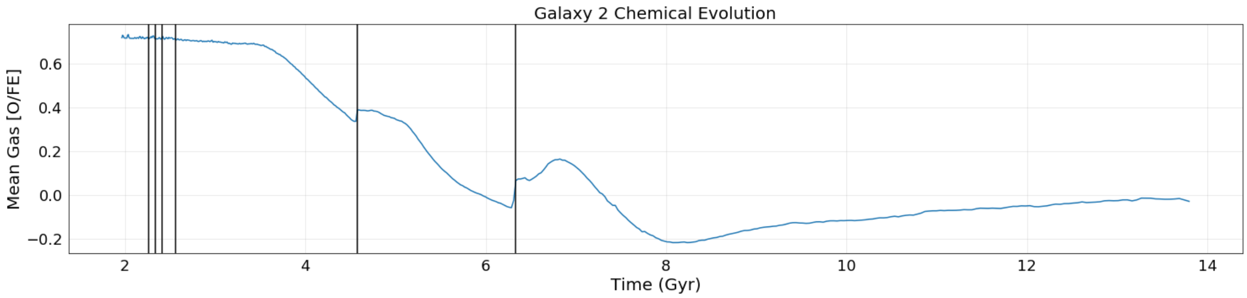
The generally flat area between 6 and 8 billion years is what I classify as a pleteau. These, too, are often associated with an accretion event, but are quite different than an inflection. Plateaus are longer term, but temporary, increases in the [O/Fe] of a galaxy. Clearly, an accretion event might have a variety of impacts on the evolution of a galaxy.

The final type of feature I identifed is a longer term increase in the [O/Fe] at later times. This only occurs in galaxies 1 and 2. It is best demonstrated by galaxy 1:



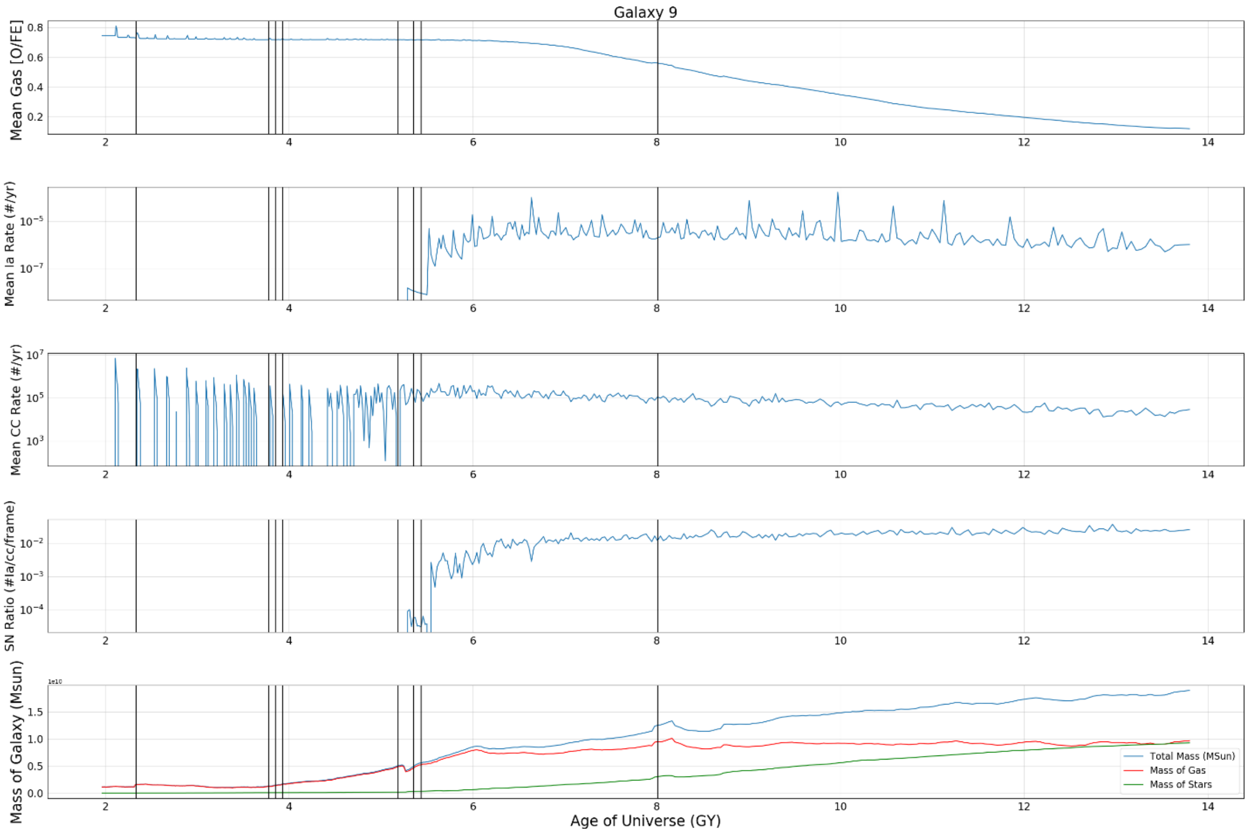
The [O/Fe] appears to complete the downward trend common to all galaxies by 10 billion years. Afterwards, the [O/Fe] begins to increase. It should be noted that there is also a plateau in galaxy 1 that is not associated with an identified accretion event. It is likely that there was an accretion event, but one that was so small that it was not identified. I investigate this feature in more detail later.

A sythnthesis of all four features, the “decrease,” the “inflections,” , “plateau”, and “tail”, can be seen in galaxy 2.



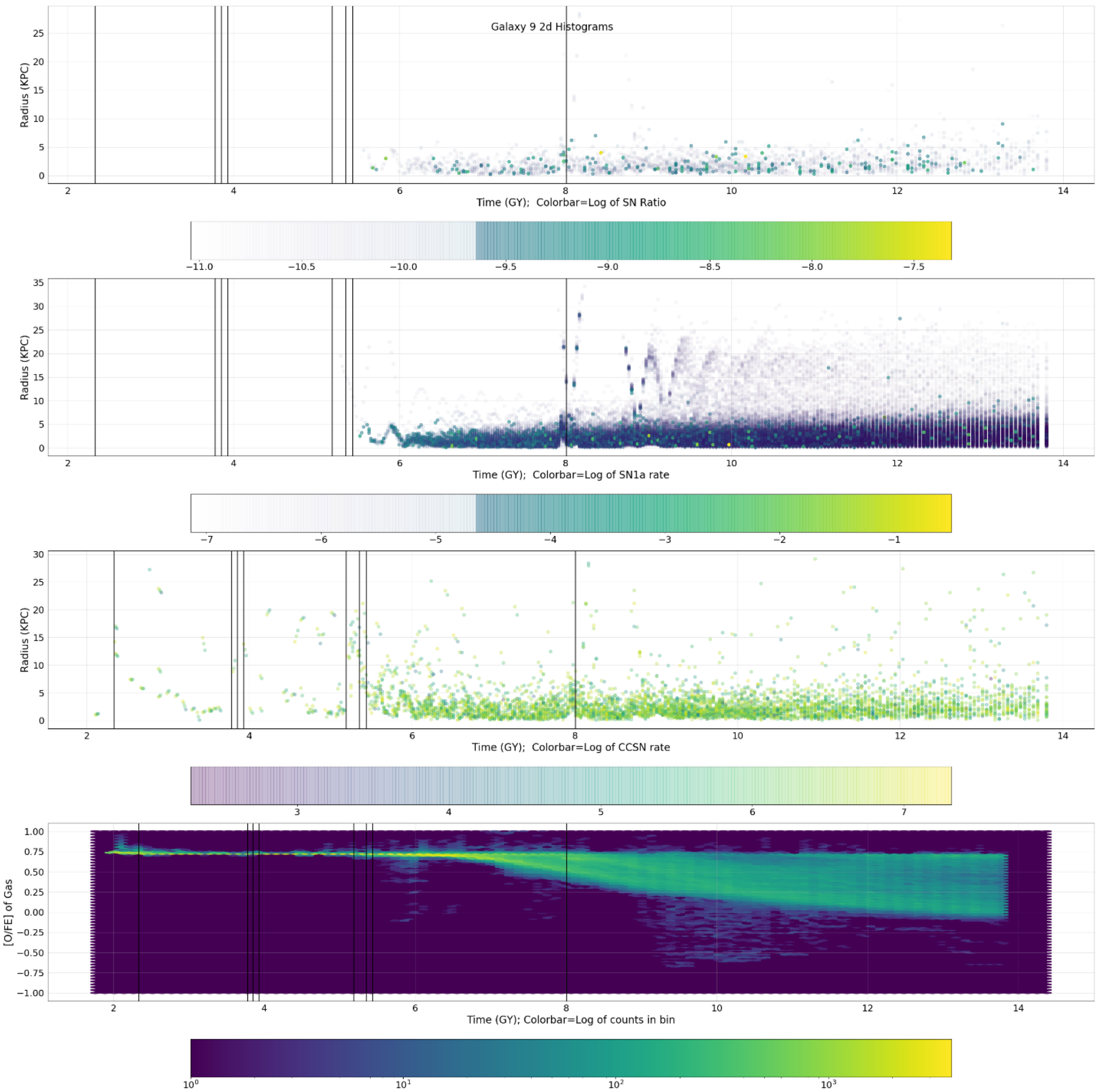
Like the other galaxies, galaxy 2 trends downward in [O/Fe]. There are large inflection points associated with accretion events, and each accretion event has a plateau associated with it. Finally, there is a tail associated at longer times.

In order to better understand these effects, I examined other aspects of galactic evolution. Specifically, I examined the mean core collapse supernova rate, the mean supernova Type Ia rate, the SN ratio, and the mass of the galaxy. These values were chosen because of their large impact on the chemical evolution of a galaxy. The following are these values for the general case, galaxy 9:



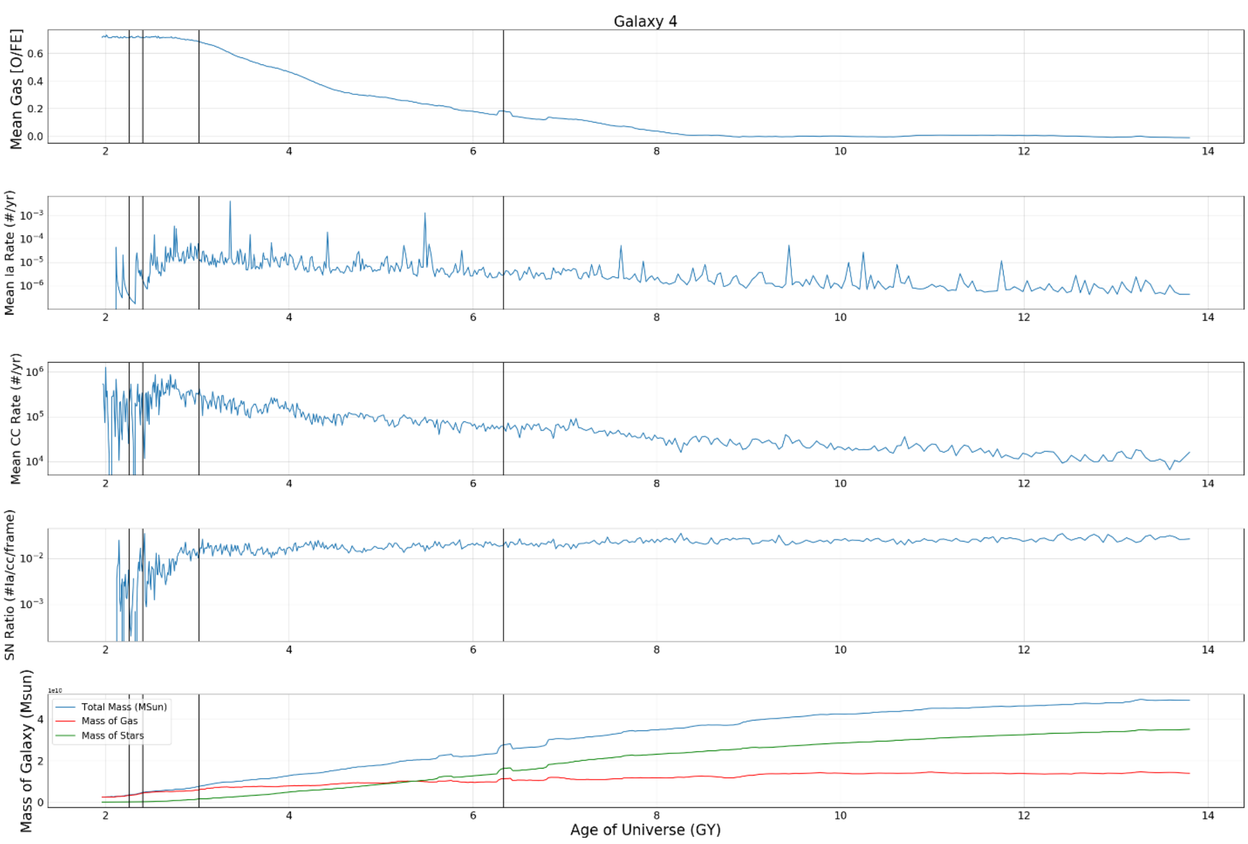
The factor that appears to contribute the most to the evolution of the galaxy is the supernova rates. While CC SNs do happen before 6 billion years, supernova generally only occur after approximately 6 billion years. This coincides with the beginning of the decrease in [O/Fe.] Furthermore, the ratio in the amount to of supernovae is fairly constant after this time. The effect of the accretion event at 8 billion years can be seen in the mass plot, does not coincide with any significant change in the other values.

I also plotted the supernova rates and ratios on a per-particle basis. Below are two dimensional scatterplots of the supernova rates. Each point represents a star particle. The y-position represents the galactocentric radius and the color represents the supernova rates. The final plot is a 2d histogram of the gas particles. The y-position represents the [O/Fe] of the particles and color corresponds to number density. Since many stars have a supernova ratio that is an invalid value (i.e., some constant over zero), the star particles shown in the graph do not represent the total number of particles in the frame.



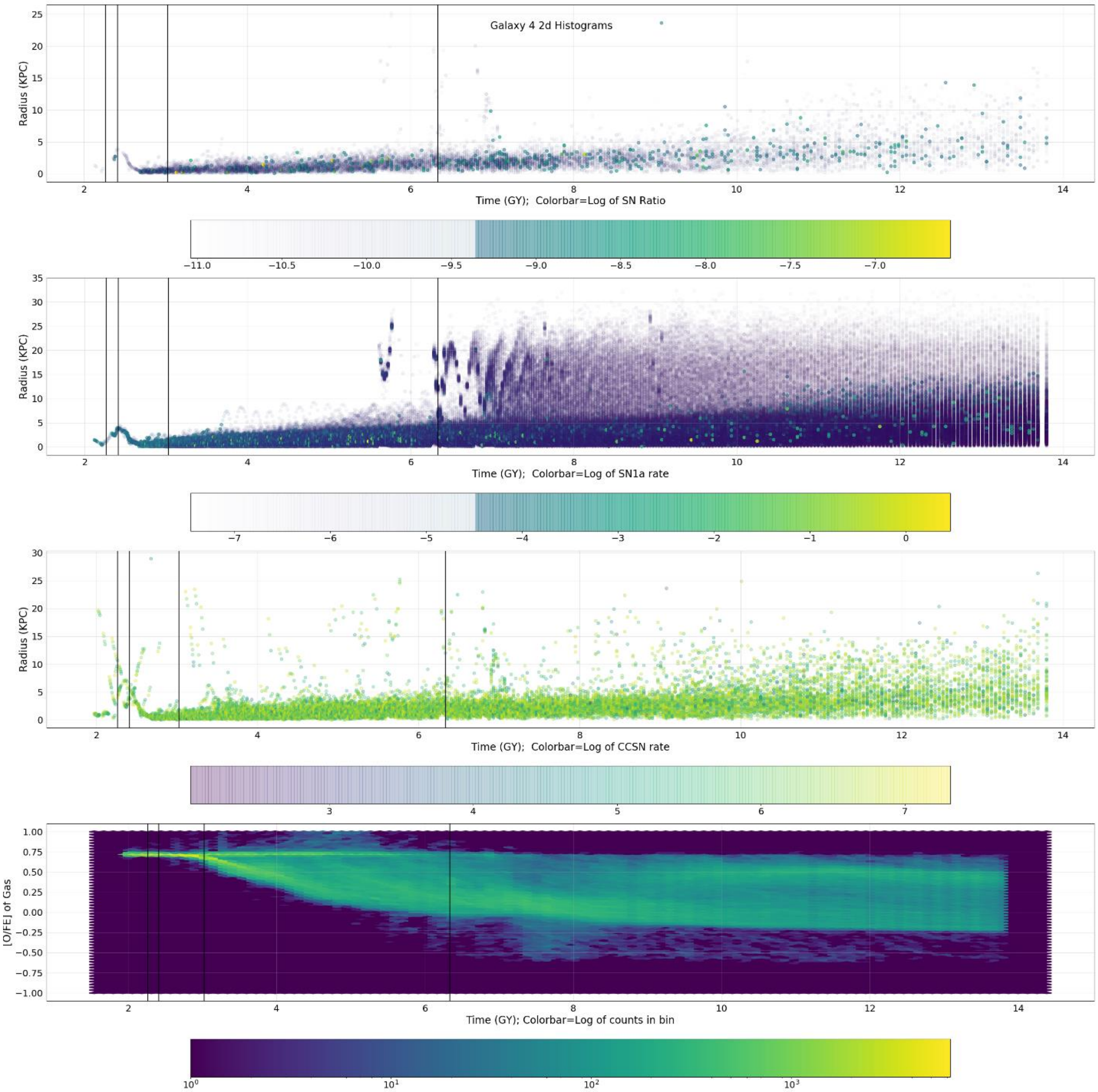
There are three key points to be observed from this plot. This plot shows that the supernova rates are more-or-less constant in time, much the same as in the previous plots. In addition, the supernova, when they do occur, are mostly confined to the innermost regions of the galaxy, less than 10 kiloparsecs from the galactic center. A second key point is that at early times before the supernova happen, the gas is almost homogenous in terms of [O/Fe]. When both types of supernovae do begin, a spread is seen with many gas particles becoming more and more alpha poor in comparison to their iron content. Finally, the accretion event at 8 billion years can be seen in the [O/FE] histogram as a bright over-density within the spread of the gas. The position of this over-density provides an explanation as to why the event had such a small effect on the [O/Fe], but still caused a noticeable change in the mass of the galaxy: the over-density is very near to that of much of the other gas in the galaxy. This means that the composition of the incoming gas is similar to the galaxy already, causing only a slight change in the overall abundance.

Next, the history of galaxy 4 is investigated. Plots of the same parameters are shown below:

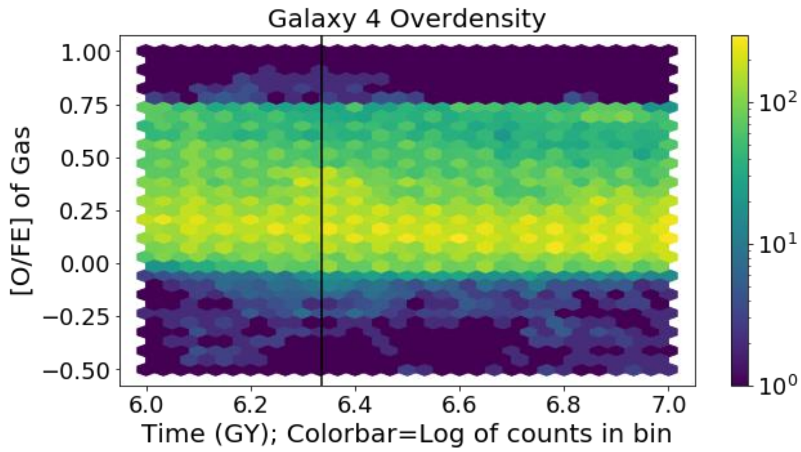


In this case, both types of supernovae begin at much earlier times than galaxy 9. This corresponds with an earlier decrease in [O/Fe]. Furthermore, the rates of both types of supernova decrease much more dramatically over time, though the ratio of total Ias to total CC SNs in each frame remains fairly constant. It should be noted that unlike galaxy 9, the majority of the mass contribution in galaxy 4 comes from the stellar mass, and not the gas mass. In fact, I found that generally, the more massive the galaxy, the greater the fraction of mass consists of stars at the end of the simulations.

Below are the plots of the same quantities in individual particles as before.

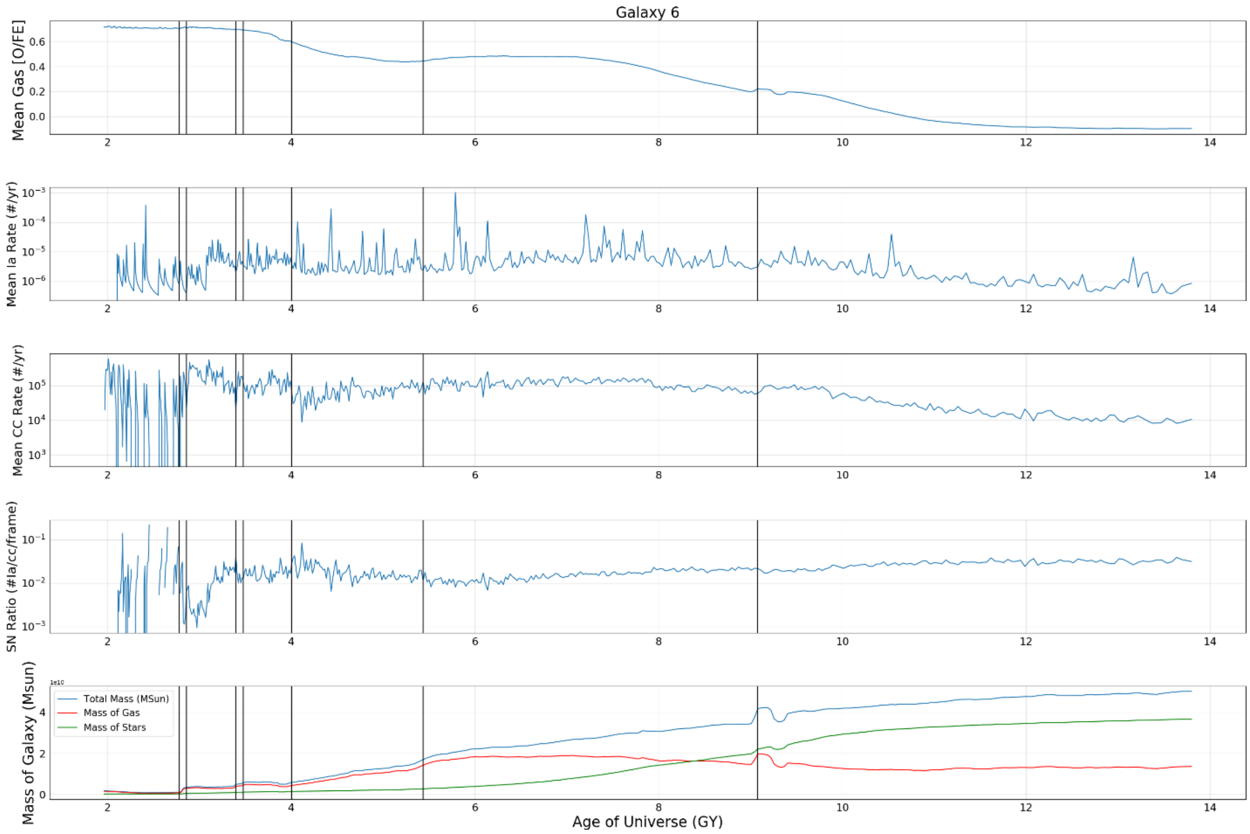


Again, the supernovae are relatively constrained to the inner regions of the galaxy, though this is less true at later times. The time where an accretion event is identified (and at the point of inflection), an over-density in the gas histogram can be seen. This case is different than that of galaxy 9, however. Here, the composition of the over-density of gas is fairly different than the majority of the gas. Where much of the existing galaxy has [O/Fe] near 0.1, the over-density, and thus the accreted gas, has an [O/Fe] of about 0.4. This is significant enough to raise the [O/Fe] of the galaxy as a whole.



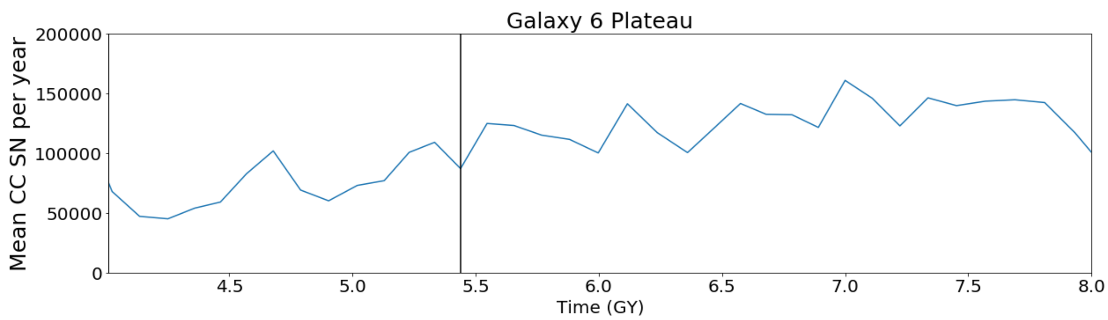
A close up of the accretion event in galaxy 4. Notice the sudden appearance of a population of gas with an [O/FE] of 0.4

I then investigated galaxy 6 to explore the plateaus associated with the accretion event, and to contrast other features associated with the plateau and the inflection. I plot the same values as before.



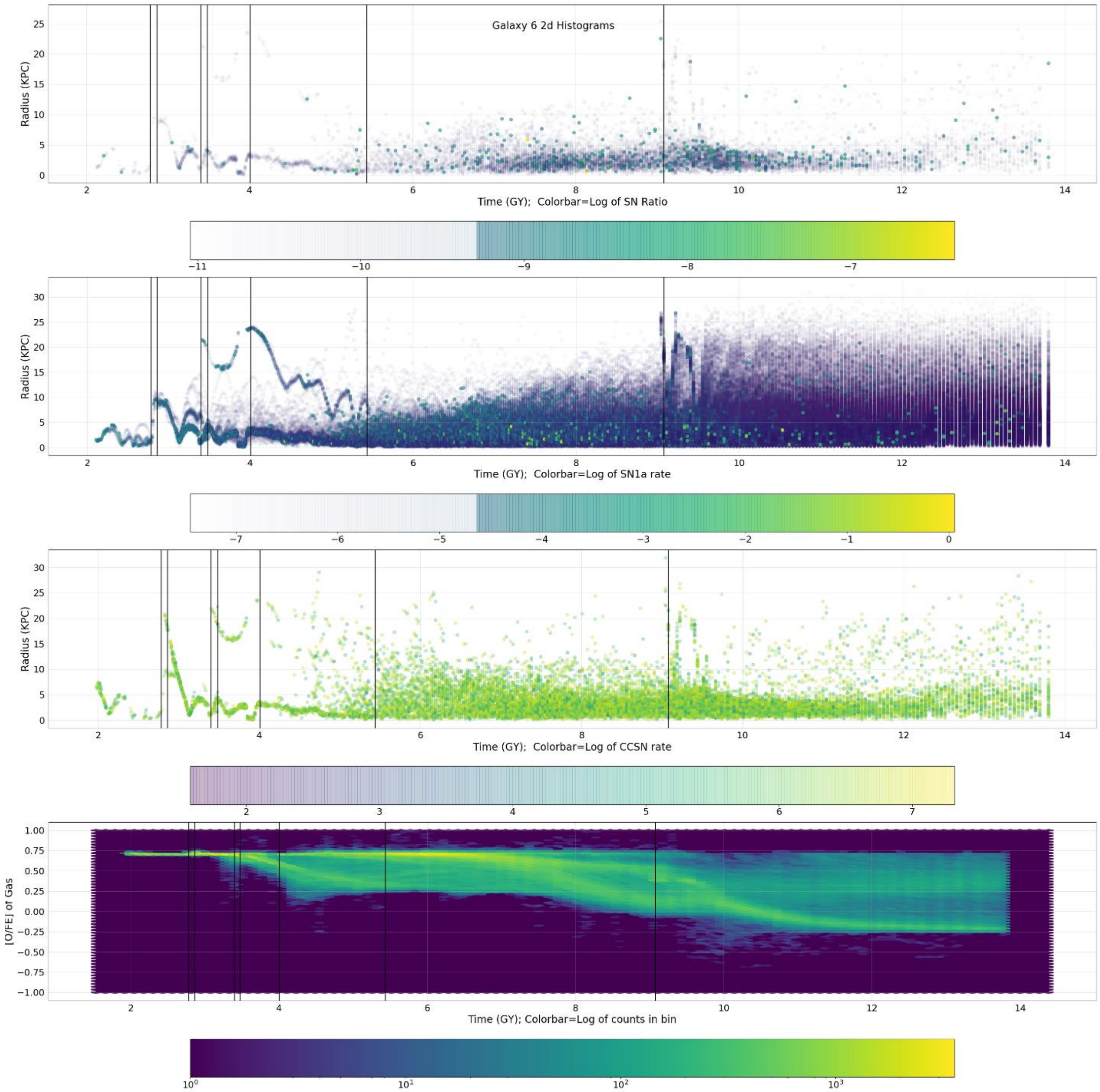
The first notable difference between the inflection and the plateau in this galaxy is the change in galactic mass due to the accretion events. With the inflection, the mass of the gas varies wildly as a merging galaxy suddenly appears, disappears, and reappears in the frame. This does not happen in the merger associated with the plateau, and furthermore, the gentler increase in the total mass in the frame suggests that galaxy 6 did not merge with a large satellite, but steadily accreted gas over time, though still quickly enough for this accretion to be identified.

There is an increase in core collapse supernovae associated with the plateau that is not associated with the inflection. After the accretion event, the mean CC SN rate of the galaxy increases by about a factor of 3 about 0.5 billion years after the merger. The ratio of Type Ia supernova to that of the core collapse supernova noticeably decrease0 as well. An explanation for this effect is that the accretion event stimulated star formation , and the abundance of new, young stars that promptly died in a supernova. This would have the effect of raising the [alpha/Fe] of the ISM, since there was now a much greater increase in oxygen mass in the ejecta of supernova to the mass of iron from the ejecta compared to the iron mass. As the stars born in the accretion event eventually all die, there are no more supernova associated with this event. This raises the Type Ia to core collapse ratio over time. A higher fraction of the total ejecta mass throughout the galaxy would be from iron, driving down the [O/Fe]. This can be seen in the fact that after some time, the [O/Fe] trend continues the typical decrease before it is interrupted by the second accretion event is addition evidence for this interpretation.



Detail of the CC SN Rate about the first merger. Notice the increase from ~50,000 SN per year to 150,000 per year

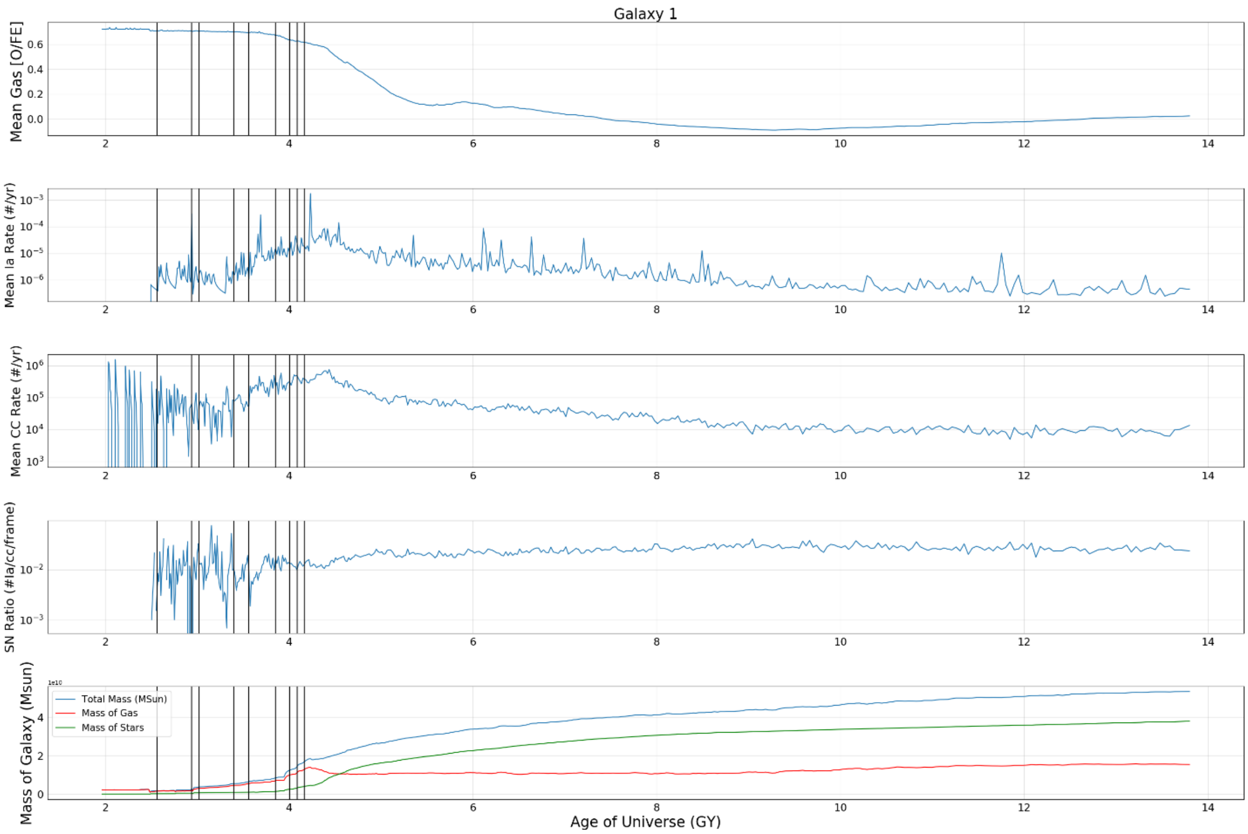
The accretion events can also be seen in the 2D particle plots.



Unlike the previous galaxies examined, the supernovae are not confined to the inner regions of the galaxy and are not constant in time. There is a dramatic increase in supernovae after the accretion event, as the over-density of color in the SN Ia plot after the event and an increase in the radial range of stars that undergo core collapse supernova. There is also a marked increase in particles for which a valid (e.g. non-infinite) supernova ratio can actually be calculated. While both Ias and core collapse supernova are stimulated, this stimulation causes more supernova than Ias, as it appears that, after the accretion event, core collapse supernovae occur at more than twice the radial range that supernova Ias are occurring. The second event is not associated with such an increase in supernova, certainly not to the degree that is associated with the plateau.

The final difference between the accretion events can be observed in the gas histogram. The same sort of over-density observed before in galaxy 4 can be seen in the second accretion event of galaxy 6, but not in the first. In that case, the over-density does not appear all at once. Instead, the fraction of particles that have a high alpha to iron abundance gradually increase over time., from about 4 to 7 billion years at the time associated with the resumption of the normal decrease in [O/Fe], this over density begins to decrease more at less at once, indicating that it is generally a specific population of gas. The information gleaned from galaxy 6 points to an explanation of a plateau that involved an increased core collapse supernova rate caused by the accretion of large mass of intergalactic gas over longer periods of time.

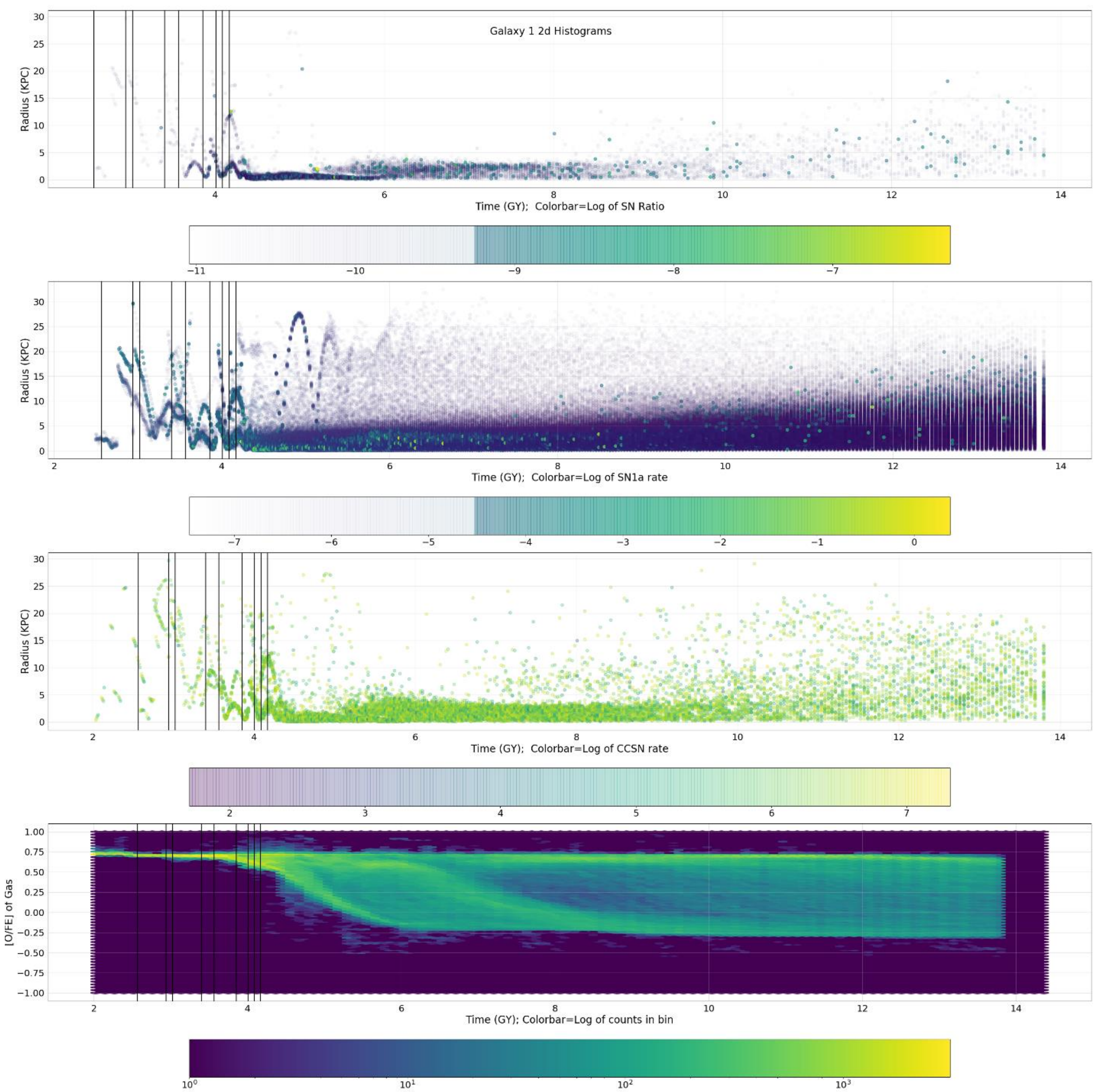
The final feature I investigated was the tail. The best example of this feature was in galaxy 1, shown below:



There is also a plateau associated with galaxy 1 that is not associated with an accretion event. This is most likely because the incoming gas has a similar effect as in galaxy 6, but at a reduced mass compared to the mass of galaxy 1. Based on the timescales of the plateau in galaxy 6, I do not think that this feature should have any significant effect on the tail. The plateau in galaxy 6 lasts for about 2.5 billion years, and in galaxy 1, the tail begins about 4 billion years after the plateau.

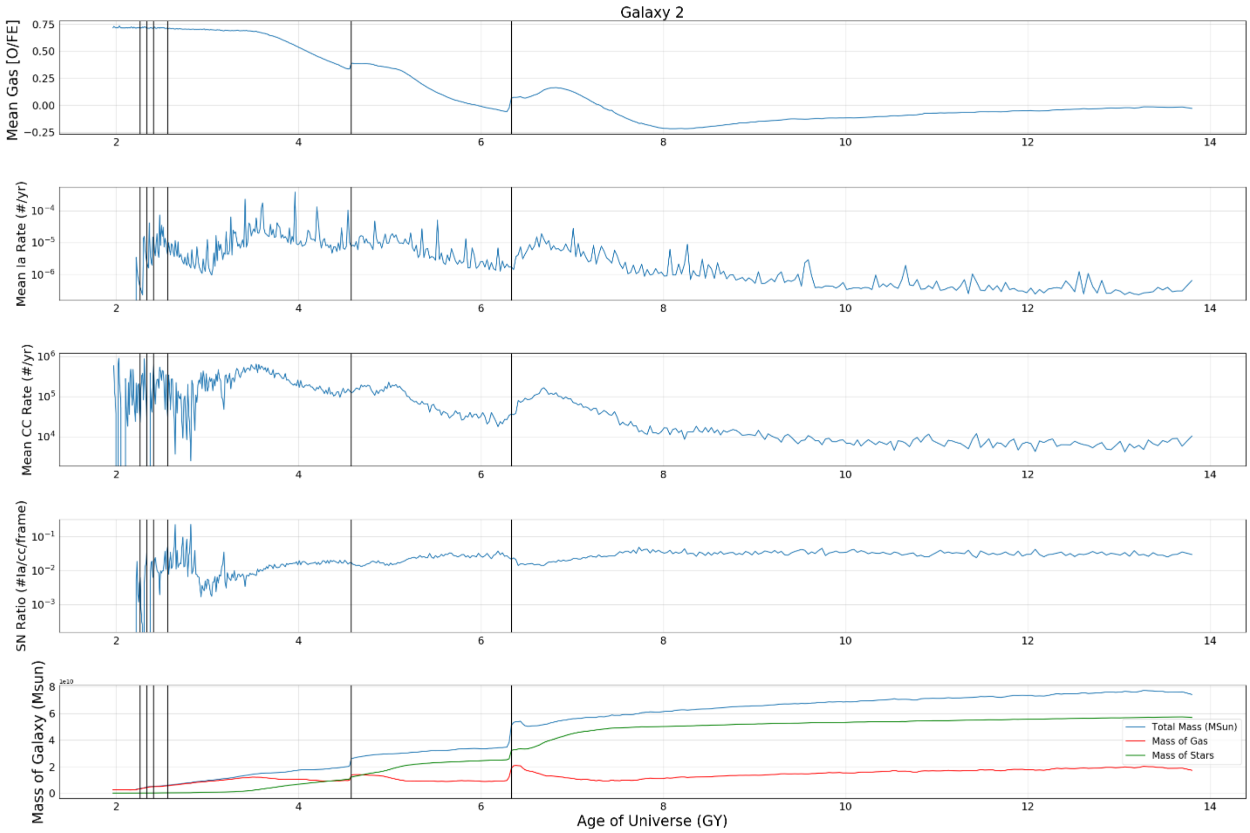
Over the course of the galaxy's lifetime, the rate of both core collapse and Type Ia supernova decrease dramatically. Since both the mean Ia rate and mean cc supernova decrease at about the same amount, the SN ratio remains mostly constant until about 12 billion years, where upon it decreases slightly, indicating a reduced amount of Ias compared to core collapse, raising the [O/Fe] of the ejecta.

Because the change in the SN ratio is so slight, a likely explanation is a long-term trend of alpha-rich infalling gas that gradually raise the [O/Fe] of the galaxy as a whole. However, the total mass of the galaxy, while it does increase at the time of the tail, does not do so in a significant way. Furthermore, when looking at the gas histogram, there is no over density of gas at any particular abundance that is only associated with the tail.



The particle plots, however, provide evidence for an alternative explanation. At the times associated with the tail, star particle in a wider range in radius undergo supernovae, even if though there are fewer supernovae overall. This is similar to the effects of the plateau in galaxy 6, though over a much longer span of time. This also does not require an over-density of gas at any particular abundance, as the accretion event’s main effect is to lower the SN ratio. From these graphs, an explanation for these tails is that they are actually plateaus, only the accretion is happening slowly enough to not trigger a more significant starburst event.

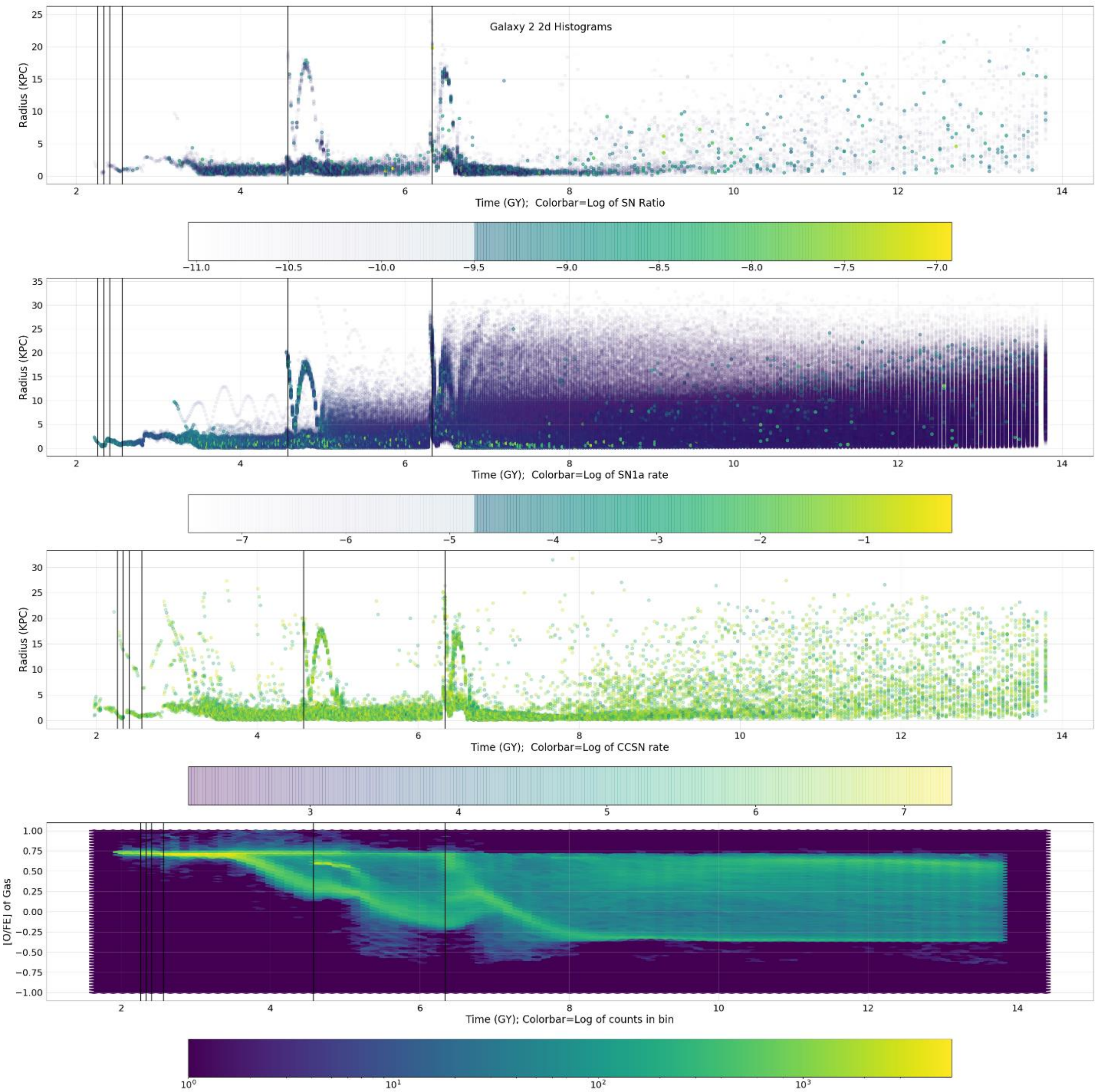
Galaxy 2 includes all the features mentioned before. I examined the features found on its abundance plots to see if the patterns I described hold true.



The most significant feature of galaxy 2 are its large and violent accretion events, here identified as galactic mergers, that increase the mass of the galaxy significantly, and are both associated with inflection points and plateaus. The plateaus themselves are also associated with a greatly increased supernova rate in both SN Ias and CC SN. This is most evident in the second, larger merger. Even so, the core collapse rates are still the most affected by these mergers: the ratio of Ia to core collapse supernovae still decreases, especially after the second merger. Such a decrease is associated with the first merger, though it returns to the baseline rather quickly.

Finally, this ratio seems to trend slightly downwards at later times, which corresponds to the development of the tail, just like in galaxy 1.

The 2d scatter plots are of particular interest, especially compared to those of galaxy 1:

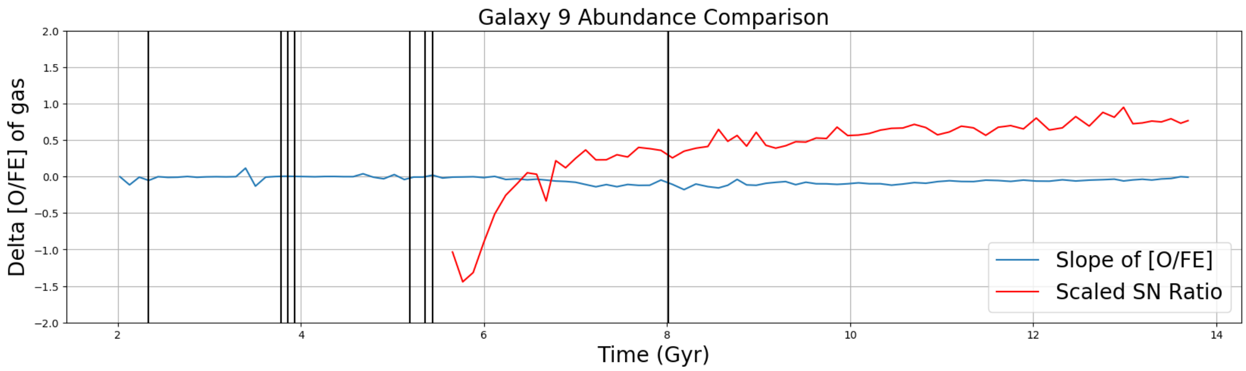


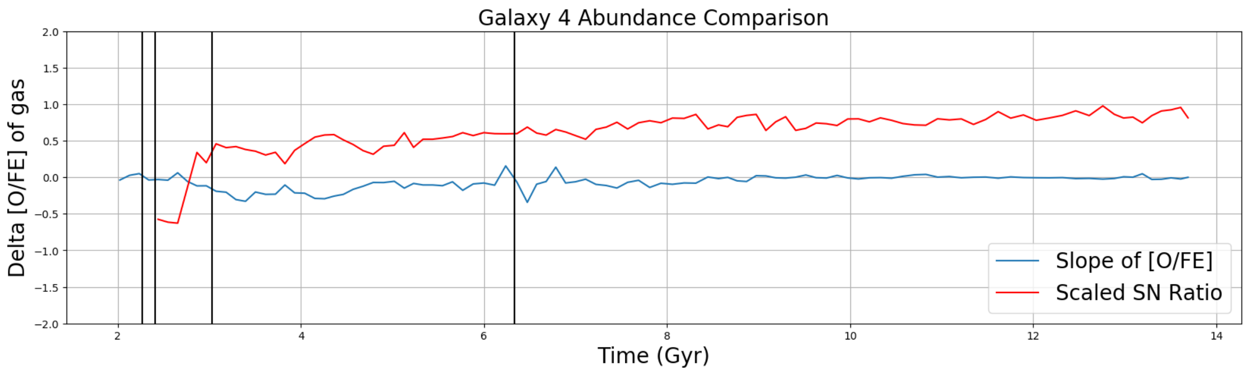
The over-densities associated with the larger mergers appear all at once as new galaxy enters the simulation frame, explaining the large inflections associated with them. Both mergers are associated with an increase in the range of the galactic radius at which supernovas happen, as well as the total amount of supernova. Again, at timescales associated with the tail, this range grows further. However, unlike in galaxy 1, there is an over-density found in timescales associated with the tail, one associated with a high oxygen content. This over-density grows in number-density even as the supernovae associated with the larger merger fade away. This feature in the histogram resembles the plateau in galaxy 6 more than it resembles the tail on galaxy 1, giving credence to the idea that a tail is simply a plateau happening at long timescales.

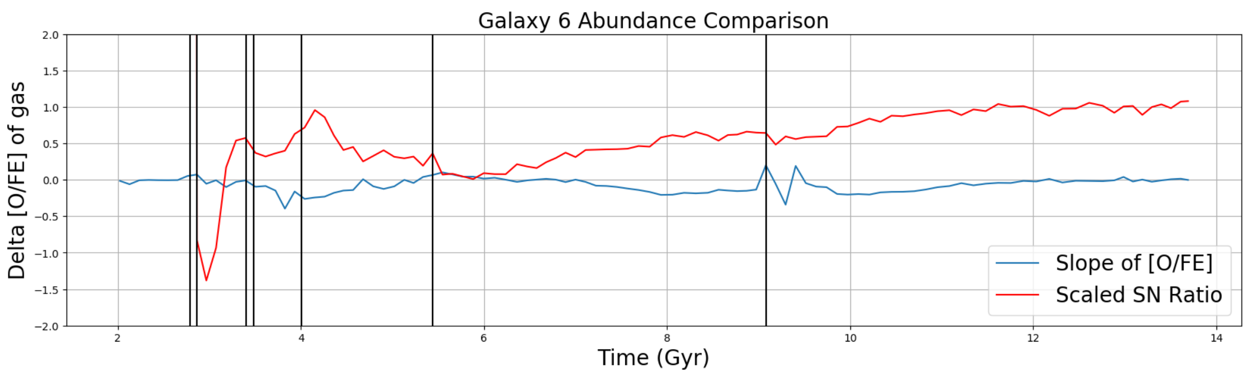
Three out of the four features- the decrease, the plateau, and the tail- seem to be directly associated with the change in SN ratio. Since a supernova causes a change in chemical abundance per timestep, I compared the slope of the [O/Fe] of each galaxy with the supernova ratio to investigate this further.

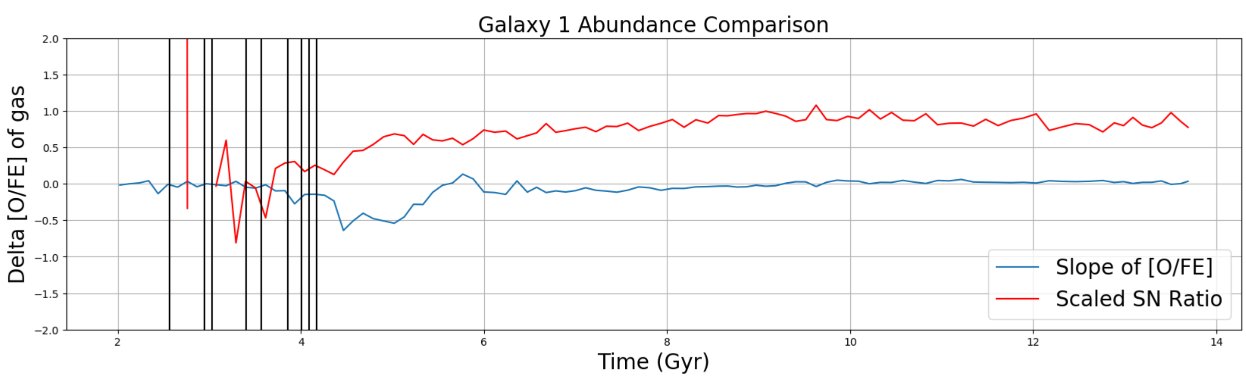
If my assumptions about the relationship of the SN ratio to the [O/Fe] of the galaxy is true, then at times where the [O/Fe] is increasing, there should be less SN Ias per CC SN, so the supernova ratio should be decreased. When the [O/Fe] decreases more quickly than normal, the supernova ratio should be increased. If the slope of [O/Fe] is zero, the SN ratio should be constant. It should be noted, however, that a constant SN ratio would not necessarily correspond in turn to a constant [O/Fe]. It would be the actual value of the SN ratio that determines the slope of [O/Fe].

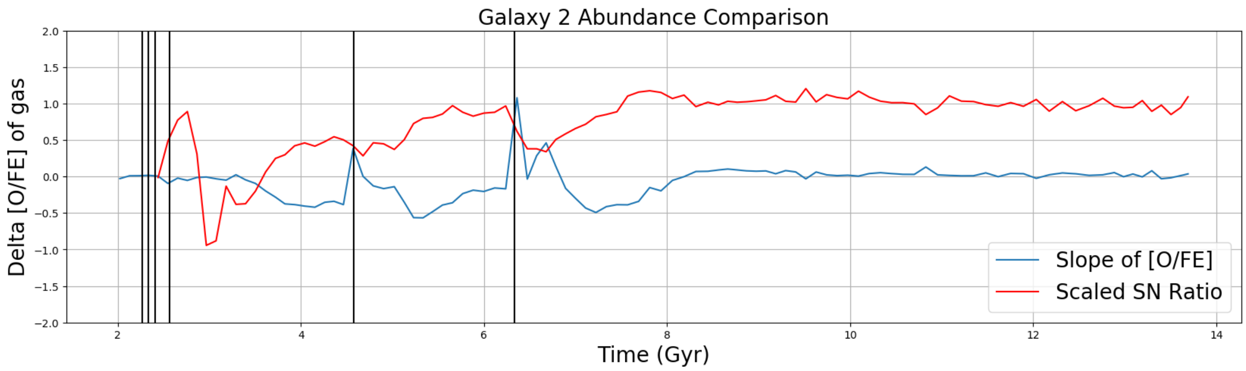
To better compare the SN ratio to the abundance ratio, I binned both values in timesteps of 100 million years so that longer term trends can be seen. I also took the logarithm of the SN ratio plus 2, and multiplied that by 2, so that the two values can be shown on the same scale and thus be compared more clearly.


Galaxy 9 Abundance Comparison
Delta [O/FE] of gas
Time (Gyr)
Slope of [O/FE]
Scaled SN Ratio


Galaxy 4 Abundance Comparison
Delta [O/FE] of gas
Time (Gyr)
Slope of [O/FE]
Scaled SN Ratio


Galaxy 6 Abundance Comparison
Delta [O/FE] of gas
Time (Gyr)
Slope of [O/FE]
Scaled SN Ratio


Galaxy 1 Abundance Comparison
Delta [O/FE] of gas
Time (Gyr)
Slope of [O/FE]
Scaled SN Ratio

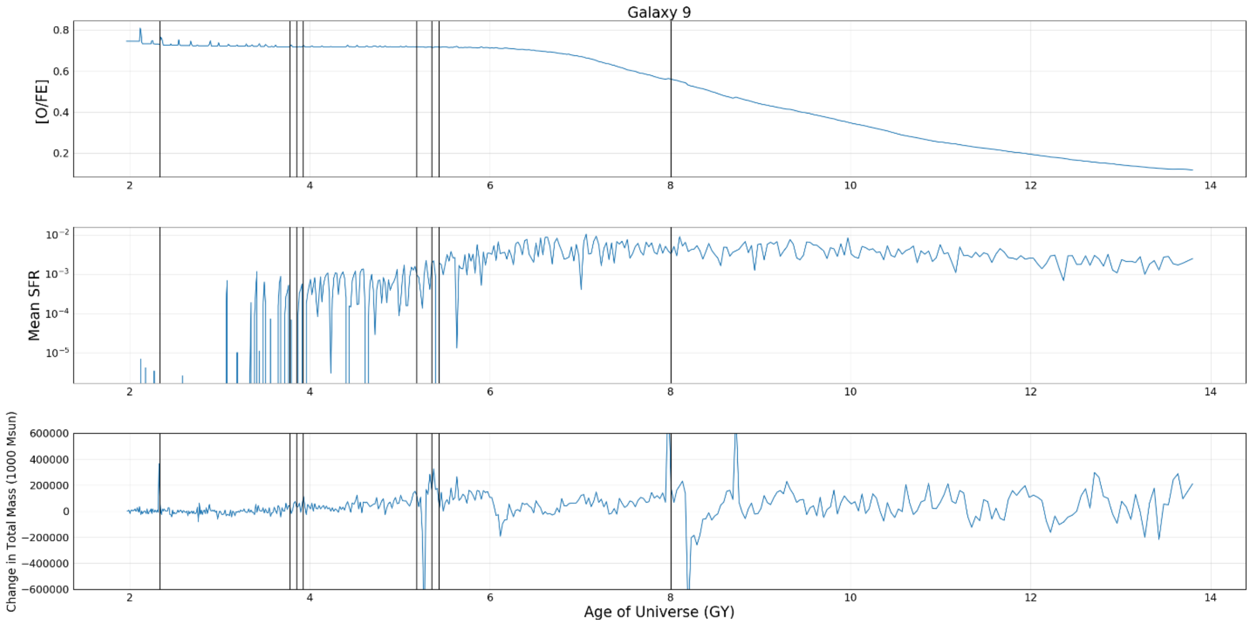


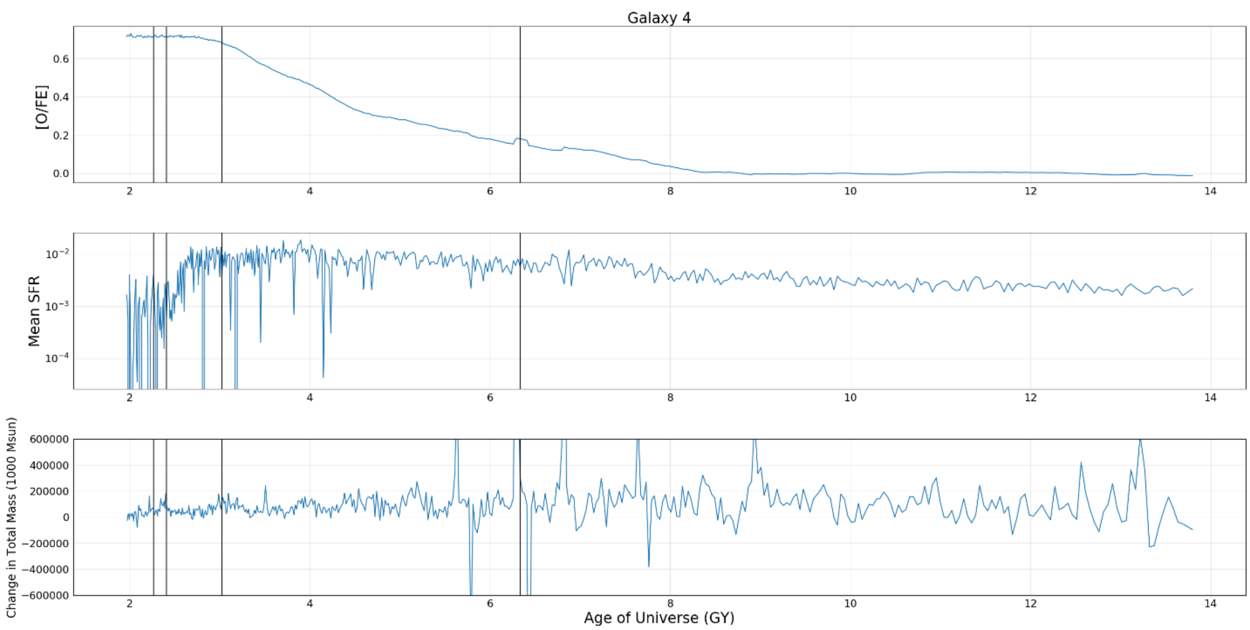
Generally, I find this prediction to be true. In galaxy 6 and 9, an increase in the ratio at about 6 billion years corresponds to a decrease in [O/Fe]. My prediction does not hold true for the early times of galaxies 1 and 2, but as was stated, the small population sizes might cause unexpected effects on the data. In galaxies 1, 2, 4, and 6, there is marked increase in the SN ratio corresponding to be beginning of the decrease in [O/Fe]. This is most evident in galaxy 6 and 1. In galaxy 1 and 2, the SN ratio decreases very slightly at times greater than 10 billion years, corresponding to the tail features. Finally, in galaxy 2 and 6, there is a significant decrease in the ratio at the time of the mergers for which there is an associated plateau which matches the idea that the accretion event stimulated a starburst.

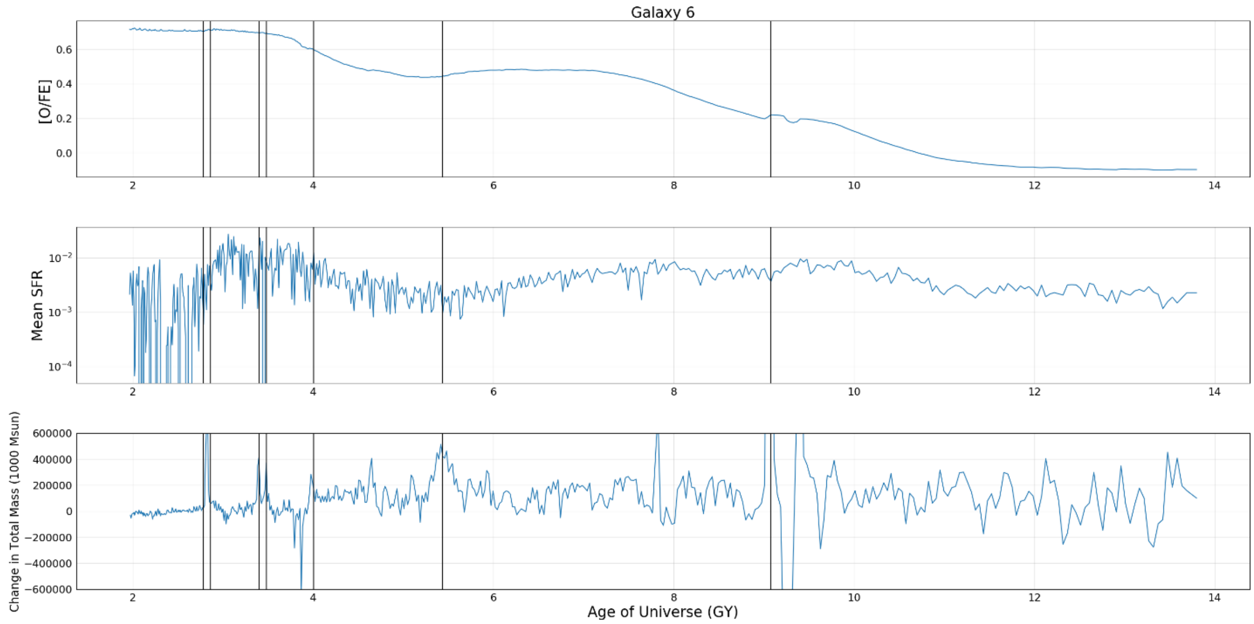
The two values, however, track correlate less closely as time goes on. This is most likely due to the differences between core-collapse and Type Ia supernovae. In the simulation, all SN Ias have the same yield. The core collapse supernova, however, can happen in stars with a wide range in mass and metallicity. As the galaxy evolves, stars that are born at later times will have a different elemental composition. This composition effects their yields, and the simulation models this using yields given by Kobayashi (2011) . Furthermore, as a star particle grows older, the mass of the stars that are going supernova decreases as well. This too, affects the nuclear synthetic yield of the supernova. Therefore, as the galaxy and star particles evolve, though the supernova ratios might be constant, the ratio of the oxygen and iron ejected from the supernova will not be constant.

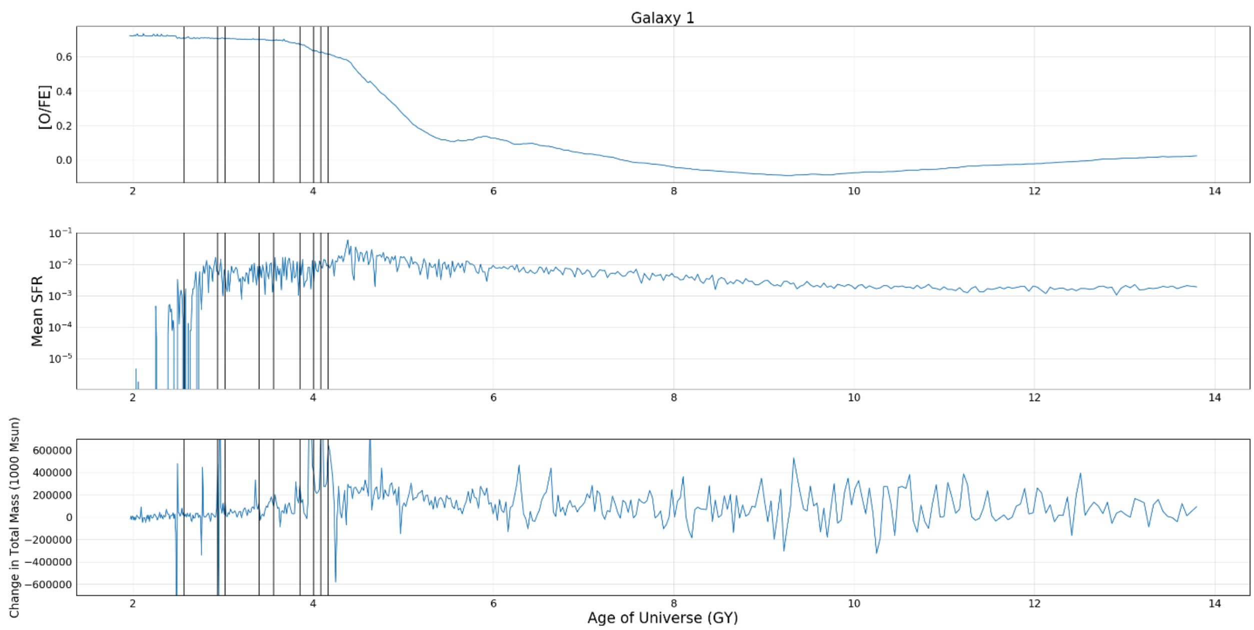
This might be an alternative explanation for a tail: that there is not a stimulation of more core collapse supernova- the yields change enough to produce such an effect at the same supernova ratio. However, this is unlikely for two reasons. The first is that there is in fact a change in the supernova ratio, albeit a slight one. The second is that a tail is not seen in most galaxies, even those whose total amount of supernova stays roughly constant. This indicates that there is some event that causes a tail that is either unique to galaxies 1 and 2, or at least causes a unique effect in galaxies 1 and 2. For this reason, and the fact that the above plots generally agree with my prediction, that I find my explanations of the described features to be generally true.

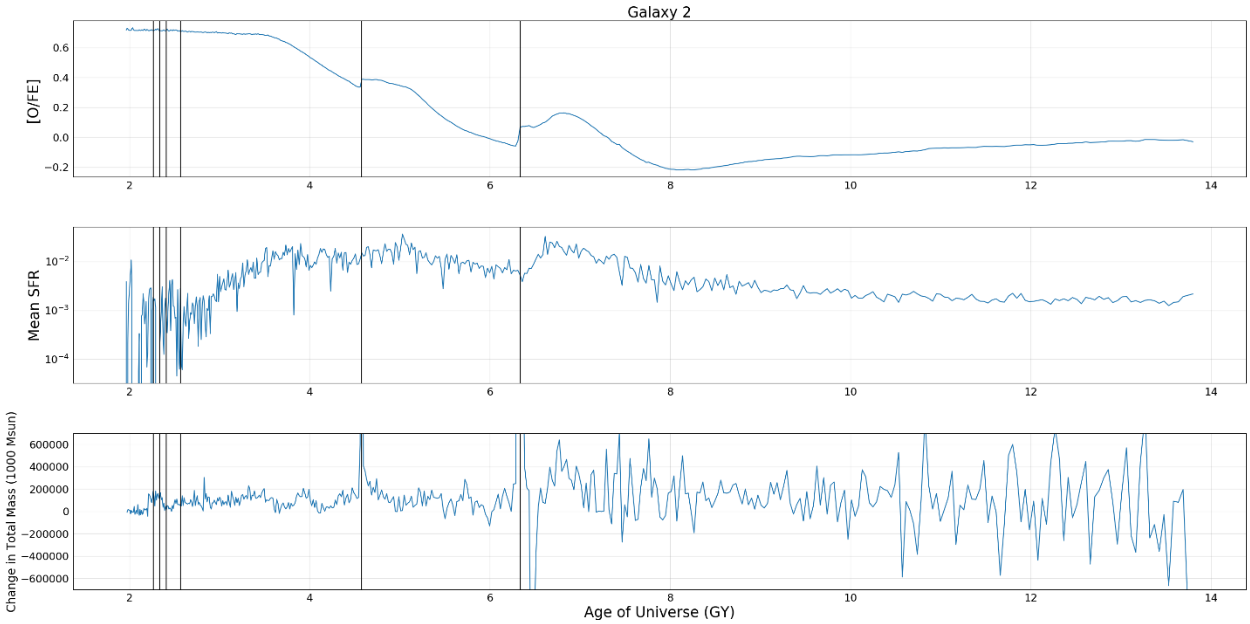
One final investigation I did was to compare the supernova ratio, the change in mass of the galaxy, and the mean star formation rate of the gas to the [O/Fe]. Since my explanation for both the tail and the plateau involve an increased star formation rate due to some accretion event, it follows that in areas of a plateau and a tail, there should be some increase or elevation in the mean SFR, as well as a positive amount of infalling gas. The following are these comparisons for the 5 galaxies:


Galaxy 9
[O/FE]
Mean SFR
Change in Total Mass (1000 Msun)
Age of Universe (GY)


Galaxy 4
[O/FE]
Mean SFR
Change in Total Mass (1000 Msun)
Age of Universe (GY)


Galaxy 6
[O/FE]
Mean SFR
Change in Total Mass (1000 Msun)
Age of Universe (GY)


Galaxy 1
[O/FE]
Mean SFR
Change in Total Mass (1000 Msun)
Age of Universe (GY)



The results are somewhat as expected. In the generic galaxy, star formation rate is highest at the birth of the galaxy, and slowly decreases over the course of its life. In the plateau regions, there is indeed an increase in star formation beginning at the merger, and this starburst reaches its highest intensity at about .5 billion years later, corresponding to the highest point in the plateau. There is also a marked increase in the total mass of the galaxy in both the infections and plateaus.

The tails, however, differ from my expectations. Whereas in the classical example, the star formation rate decreases more or less constantly in log space over time, in areas with a tail, the SFR remains steady. This corresponds to the explanation that stimulated star formation is the cause of the tail. However, it is not correlated with any significant change in the accretion rate. It does not seem to be distinguishable from the general case, at least not in a way that is consistent across both galaxy 1 and 2. Therefore, while I still find that the plateaus are caused by a starburst following an accretion event, a tail is most likely caused by a stimulation in star formation *not* due to accretion. Tails are not simply long-term plateaus and are instead specific features of in their own right.

Conclusion

I identified three ways in which the mean [O/Fe] of gas in these simulated galaxies differ from the general case. There may be an inflection, a sudden jump or decrease in the abundance ratios over short periods of time. These are caused by a large amount of gas, which suddenly appears in the simulation frame, and merges with or very rapidly accretes onto the host galaxy. There may be a plateau, a long-term but temporary levelling-off or increase in [O/Fe]. These are caused by an increased core-collapse supernova rate, stimulated by either a galactic merger or the accretion of a large amount of gas. Finally, there may be a tail, which is a long-term increase in the alpha abundance at later times not associated with an accretion event.

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